Airborne Lidar Bathymetry: The SHOALS System

by J.L. IRISH, J.K. McCLUNG, W.J. LILLYCROP
Joint Airborne Lidar Bathymetry Technical Center of Expertise
US Army Engineer District –Mobile
CESAM-OP-J
109 St. Joseph Street
Mobile, Alabama 36602
USA

ABSTRACT

In March 1994 the US Army Corps of Engineers completed development and field testing of the SHOALS which is now in its fifth year of operation. During these five years. SHOALS has proven airborne lidar bathymetry's benefits to the navigation and coastal community. Namely. SHOALS demonstrates the ability to achieve order-of-magnitude increases in survey speed for collection of accurate, densely spaced bathymetric and topographic measurements while remaining cost- competitive with conventional survey methods. Surveying 16 km2 per hour and collecting soundings every 4 m. SHOALS remotely measures water depths using state-of-the-art laser technology. With vertical measurements ranging from adjacent beach and structure topography through depths of 40 m, this unique capability allows rapid, accurate mapping of coastal projects. SHOALS missions have had a variety of purposes. Among these are navigation. shore protection. coastal structure evaluation. nautical charting. and emergency response. This paper presents lidar bathymetry technology by describing the SHOALS system and discussing several projects surveyed to date.

SUMMARY

SHOALS (Scanning Hydrographic Operational Airborne Lidar Survey) system was developed by the US Army Corps of Engineers (USACE) as a tool for monitoring the nearshore bathymetric environments typical of their coastal projects. In this capacity, the system has been deployed at many tidal inlets, providing information concerning channel shoaling, change in shape of the ebb and flood tidal shoals, and overall patterns of sand movement. The system was used to assess the underwater performance of sand placed as part of beach fills. As the SHOALS program grew and gained field experience, system capabilities expanded to include surveying nearshore topography along with the depths. The application of this kind of data includes engineering evaluation of coastal structures, shoreline surveys, beach and dune surveys, and surveys of nearshore upland dredge disposal sites.

The speed and density of data collection with the SHOALS system makes nautical charting and emergency response ideal applications of the system. To date, five SHOALS surveys have been collected specifically for the creation of nautical charts. The high- density SHOALS data allow hydrographers to accurately position navigation hazards. As part of an emergency response effort, SHOALS was used to accurately assess damage due to storms and ship groundings. The one-to- one processing time for SHOALS data provides a quick turn-around from collection to results, allowing emergency crews to respond rapidly.

In addition to discussing projects like the ones mentioned above, this paper will detail system components and operating procedures, and discuss system performance.

KEY WORDS

Charting, hydrographic survey, SHOALS, lidar, navigation,

1.0 INTRODUCTION

Development and field-testing of the SHOALS (Scanning Hydrographic Operational Airborne Lidar Survey) system was completed in March 1994. Through five years of operational experience, SHOALS has demonstrated its capacity as the only airbome-lidar system in the world to collect both hydrographic and topographic measurements in a single survey. The system has collected data from nearshore regions of the Atlantic and Pacific Oceans, Gulf of Mexico, Caribbean Sea, and Great Lakes. SHOALS has been used at over 230 project areas, collecting over 300 million soundings in national and international waters.

SHOALS uses an airborne, scanning, pulsing laser to deliver two frequencies of light: one reflects from the water surface and one passes through the water column and reflects from the sea bottom. Post-flight processing evaluates each set of returns to extract a depth accurate to ±15 cm. Each depth is positioned by inertial referencing and differential or kinematic GPS. The system operates at 400 Hz and allows for variable spot spacing on the order of meters.

The bathymetric and topographic data collected by the SHOALS system is used in many different ways. In navigation project management, dense data gives a precise account of volume and extent of navigation channel shoaling. The data allow condition assessment of navigation structures, both above and below the water surface. Comparison of consecutive SHOALS surveys at a single project provides information concerning the sediment pathways and transport rates that drive the processes for the nearshore system. In a similar manner, SHOALS data is a monitoring tool for beach fill projects. SHOALS data can extend from the dune, through the surf zone, and out to depth-of-closure, giving a complete data set for monitoring sand equilibration in both the cross- shore and along-shore directions.

SHOALS' rapid data collection makes it an ideal tool for emergency response and for nautical charting. For emergency response, the high mobility of the system allows rapid deployment, while one-to-one processing time ensures results within a minimal amount of time. The system has been used in this capacity to evaluate hurricane damage as well as ship grounding damage to coral reefs. High-density SHOALS data sets allow for the navigation hazard detection required for nautical charting missions. The system can cover large areas in very short periods of time, increasing the cost-effectiveness of nautical charting and regional mapping.

The following sections describe the SHOALS operating principles and system components. Typical operating conditions and system performance specifications are presented in detail. A variety of SHOALS projects are introduced to highlight the benefits of lidar bathymetry to the coastal community.

2.0 SHOALS SYSTEM

The SHOALS system uses state-of-the-art lidar (Light Detection And Ranging} technology to measure water depth (LILLYCROP et al., 1996). A laser transmitter/receiver mounted underneath the aircraft transmits a laser pulse (Figure 2.1). The laser energy travels to the air-water interface where a small portion of this energy reflects back to the aircraft receiver (surface return}. The remaining energy propagates through the water column and reflects off the sea bottom (bottom return}. The water depth is a direct function of .the time differential between the surface and bottom returns. The strength of the bottom return is affected by both bottom type and water clarity: lidar may not provide results in areas with highly absorptive bottom types or optically dirty water. Typically, lidar bathymeters will measure to depths equal to approximately three times the Secchi depth, or visible depth.

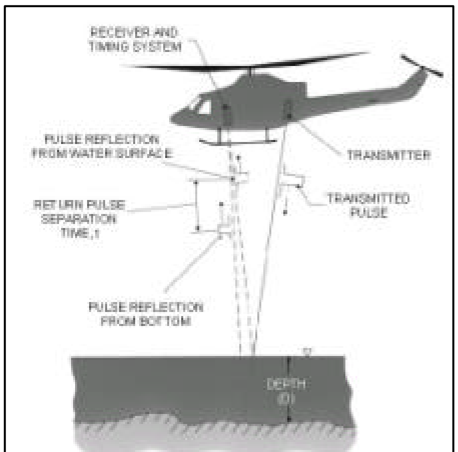

Figure 2.1

The SHOALS system is made up of two sub-parts: the airborne system and the ground-processing system. The airborne system, mountable on a variety of aircraft types, typically operates from a Bell 212 helicopter or a Twin Otter DHC-6 airplane. A pod, 270 kg and 3-m long, is mounted on the Bell 212. It houses the laser transmitter/receiver (transceiver), laser optics, inertial reference system, and video camera. When operating on the Twin Otter, the transceiver is mounted inside the aircraft. In addition, there are two consoles inside the aircraft. One console contains the operator interface including a computer screen, keyboard, and two exabyte tape drives for raw-data storage. The other console holds a video monitor and recorder, laser control panel, and aircraft positioning equipment. Coast Guard beacons and John E. Chance and Associates, Inc. STARFIX satellite system provide differential GPS (DGPS) when collecting horizontal aircraft position only. When collecting both horizontal and vertical aircraft position, SHOALS uses John E. Chance and Associates, Inc. On- The-Fly (OTF) kinematic GPS (KGPS).

In addition to the lidar depth and elevation measurements, a geo-referenced down-look video camera provides a visual record of the survey area. These video recordings are frequently used to obtain positions of coastal structures, navigation aids, piers, and other objects of interest. Additionally, the video serves as an auxiliary check for anomalous data.

Once the raw airborne data are collected, the system operator gives it to the ground processor to produce accurate water depths. The ground-processing system operates on a Sun SPARC10 workstation and uses a depth-extraction algorithm developed by the National Oceanic and Atmospheric Administration (NOM) (GUENTHER, et al., 1996). Ground processing has two functions: automated and manual processing. Automated processing extracts a water depth from each laser sounding, then applies appropriate corrections for surface waves and water-level fluctuations. Manual processing lets the hydrographer monitor data quality. The ground-processing system produces an ASCII text file with latitude, longitude, and depth for each collected sounding.

Under normal operating conditions with DGPS and conventional tide measurements, SHOALS has a vertical accuracy of ±15 cm (1σ) and a horizontal accuracy of ±2 m (1σ). Thus SHOALS easily meets both IHO (International Hydrographic Organization) Order 1 charting standards and USACE Class I survey standards. When operating with OTF KGPS, SHOALS horizontal accuracy improves to ±1 m. Flying under typical operating conditions SHOALS collects 400 soundings per second, at a rate of 16 km^2 per hour (GUENTHER, et al., 1998). SHOALS standard products include a digital text file of project depths and elevations, contour maps, channel and structure cross-sections, beach profiles, and engineering volumes.

3.0 SYSTEM ACCURACY

3.1 Depth Accuracy

Table 3.1 summarizes SHOALS current performance characteristics. Since field-testing, the SHOALS system was compared against two alternate hydrographic systems. In April 1995, SHOALS completed a 50-km^2 survey at Tampa Bay, Florida for NOM National Ocean Service in 12 hours of flight-time collecting over 5.5 million individual depth soundings. Depths in the survey ranged from 10 to 20 meters. This same area was surveyed with NOAA ship *Mt. Mitchell* equipped with a vertical-beam echo sounder (Raytheon 6000N digital survey fathometer). This system meets IHO charting requirements and was extensively used by NOM to meet their charting needs. During *Mt. Mitchelfs* four-month deployment, the NOM ship collected 30,000 depth soundings over the same survey area. Both SHOALS

Table 3.1 SHOALS performance specifications

Maximum Depth	60 m (or 2 to 3 times the Secchi depth)
Vertical Accuracy	±15 cm
Horizontal Accuracy	
DGPS	±3 m
OTF KGPS	±1 m
Sounding Density	4-m grid to 8-m grid
Operating Altitude	200 m to 400 m
Scan Swath Width	110 m to 220 m
Operating Speed	115 to 230 m/s

and *Mt. Mitchell* obtained horizontal and vertical controls from DGPS and predicted and observed tides, respectively. The NOS compared SHOALS soundings with the acoustic soundings by mapping the *Mt. Mitchell* data onto a digital-terrain map of higher-density SHOALS data (Figure 3.1). These results confirm that SHOALS does indeed meet current IHO nautical charting standards (RILEY, 1995).

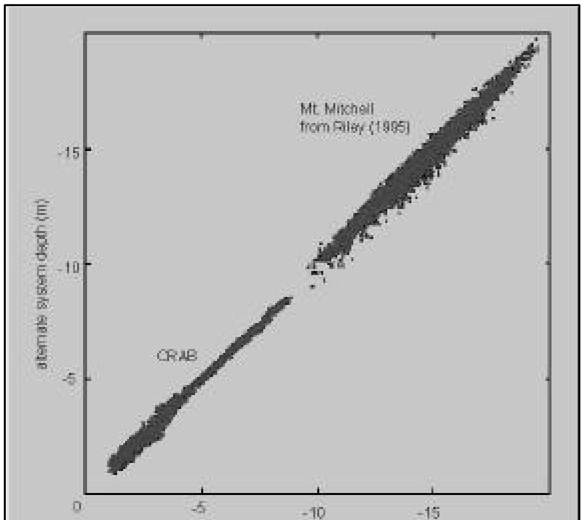

Figure 3.1

In June 1996, SHOALS completed a survey at the USACE Coastal and Hydraulics Laboratory Field Research Facility (FRF) in Duck, North Carolina. SHOALS surveyed the 2.5-km^2 area in less than one hour collecting 300.000 soundings. Laser returns in this survey range from elevations along the dry beach to nine-meter depths. Horizontal position was provided by DGPS and the soundings were vertically referenced to a NOM self-recording tide gage.

The FRF collects bathymetry monthly using the Coastal Research Amphibious Buggy (CRAB), a self-powered, 17.5 m-high, mobile tripod on wheels. In contrast to SHOALS, which used DGPS and a tide gage in this survey, the CRAB used a Geodometer 140-T self-tracking total station to determine each depth's horizontal and vertical position (BIRKEMEIER et al., 1985). This system's horizontal and vertical accuracy both are within 3 cm. A typical CRAB survey of the study area requires a couple of days to collect 21,000 soundings. A comparison between the SHOALS and CRAB data similar to that performed for Tampa Bay show an average difference in vertical measurement of 10 cm, again confirming SHOALS depth accuracy (Figure 3.1).

3.2 Volumetric Accuracy

As hydrographic surveys are the primary tool for calculating sediment volumes for navigation and beach-nourishment projects, the impact of survey density on volumetric computations was investigated (IRISH et al., 1997). Four beach-nourishment projects located on the Gulf of Mexico, Atlantic Ocean, and Great Lakes were selected for this study. Since profiles of nourishment projects are normally collected at spacings from 30 to 300 m in the US, profile data were simulated from the high-density SHOALS data. Figure 3.2 shows the 1994 SHOALS data and profile data simulated from SHOALS data at Island Beach State Park along central New Jersey's coast. This figure clearly illustrates the importance of high-resolution data in areas with complex bathymetry.

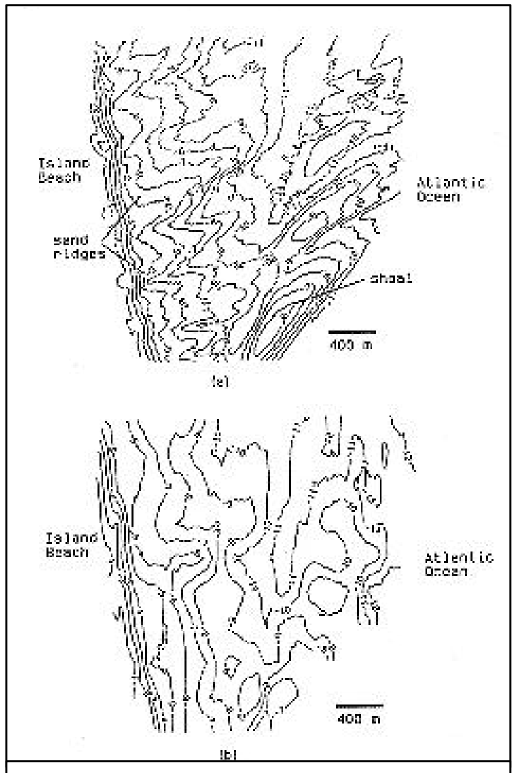

Figure 3.2

Table 3.2				
Profile Spacing (m)	Volume Difference (m^3/m)			
	Longboat Key Florida	Island Beach New Jersey	St. Joseph Michigan	Presque Isle Pennsylvania
5	0.0	0.0	0.0	0.0
10	-0.4	0.1	0.0	1.2
25	0.0	-0.1	-0.4	1.9
30	-1.8	0.1	0.2	0.8
50	0.2	-0.3	-1.7	3.3
60	-3.1	0.2	2.3	0.9
100	-1.6	-1.9	-3.3	6.1
150	-0.7	-0.3	-6.5	-10.4
200	2.2	5.3	-18.5	0.8
250	-6.6	-15.9	8.4	4.2
300	12.3	-19.8	-5.3	-9.8

Beach-fill volumes were computed for each project by employing the well-used area-end method where the cross-sectional areas of two consecutive profiles are averaged and multiplied by the distance between them. In Table 3.2, volume difference represents the difference between the volume computed with the 4-m spacing (the density of a SHOALS survey) and the volume computed with the stated spacing, in cubic meters per meter length of beach. Positive differences indicate the stated spacing resulted in a volume larger than the 4-m spacing while negative differences indicate a smaller volume. In general, the study results indicate the error in computed volume increases as profiles spacing increases. These volume differences translate to total project costs. And based on typical beach-quality sand costs ranging from \$5 US to \$30 US per placed cubic meter, the results then indicate potential cost differentials upward of \$1 million US.

4.0 COASTAL NAVIGATION CAP ABILITIES

During the past three years, SHOALS performed a wide variety of missions, many at maintained navigation projects. The USAGE is tasked with surveying and maintaining navigation projects throughout the United States, and at any given project, the USAGE is concerned with channel condition, navigation structure condition, and impacts to adjacent beaches.

4.1 Tidal Inlets

A number of these navigation projects are at tidal inlets. A typical SHOALS survey of a tidal inlet includes full coverage of the inlet from the seaward approach over the ebb shoal through the inlet throat and into the back bay. Figure 4.1 shows the SHOALS survey at Lake Worth Inlet in Palm Beach. Florida. The survey, completed in three hours by SHOALS, requires several days to complete with a conventional single-beam acoustic system. Lake Worth Inlet is characterized by a well- defined ebb shoal, a maintained navigation channel 11-meters deep, and two parallel rubble-mound jetties. From the SHOALS bathymetry and topography, USACE engineers accurately quantified channel dredging requirements, above and below-water jetty conditions, toe scour at the jetties, and nearshore conditions.

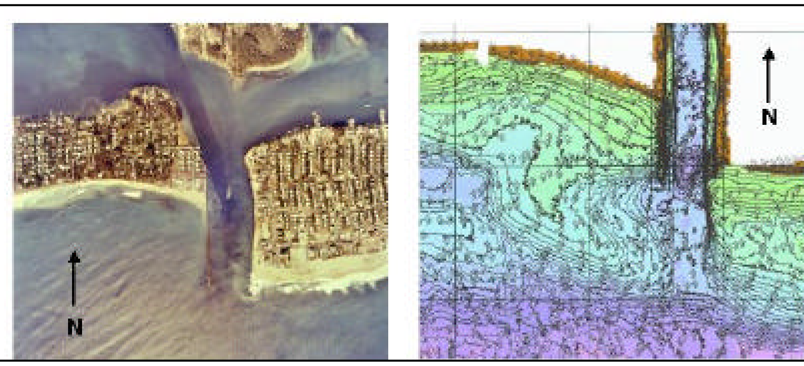

Figure 4.1

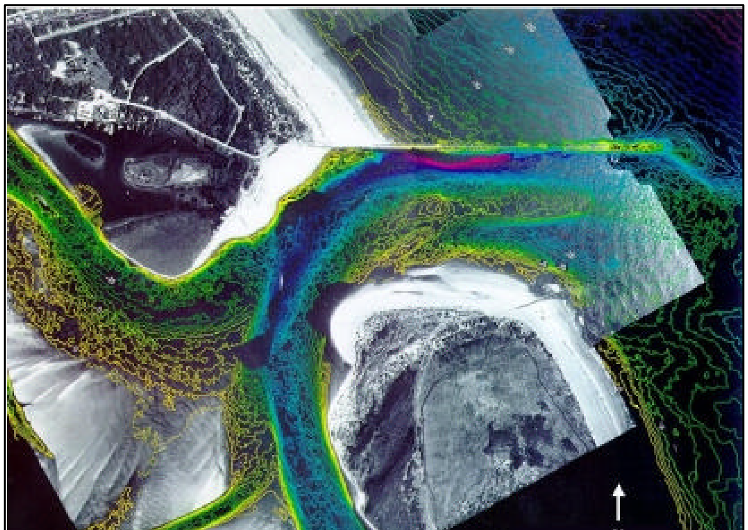

Figure 4.2

A complex back-bay channel system and migrating channel through the jettied inlet entrance characterizes Ponce De Leon Inlet, just south of Daytona Beach, Florida. SHOALS surveyed this project on three occasions collecting over two million soundings in less than six hours (Figure 4.2). The surveys quantify the severity of scour along the inside edge of the north jetty and at the jetty's tip and completely map the back-bay system. The three-dimensional complexity of the ebb shoal and adjacent beaches is also apparent. From the bathymetry and topography on the north jetty, the impacts of the scour holes on the jetty's stability were also assessed.

Shinnecock Inlet is one of six inlets located on the barrier island of Long Island, New York (Figure 4.3). This project has also been surveyed three times by SHOALS. Each survey includes data through the navigation channel and sedimentation basin, along the jetties and the revetment on the bay shoreline, and of the offshore and back bay areas. The comprehensive data coverage in the inlet's throat and over the ebb shoal reveals the depth and extent of the scour hole at the toe of the west jetty along with the scour associated with the revetment protecting the throat's eastern shoreline. The USACE Coastal and Hydraulics Laboratory to develop an historic, long-term sediment budget are using the SHOALS data along with historic data at this inlet. This project quantifies the effect of the inlet on local sediment motion. For this study, accurate definition of the ocean and bay shorelines is essential, along with accurate resolution of the shape and mass of the ebb and flood tidal shoals. SHOALS data density provides the engineers with this information.

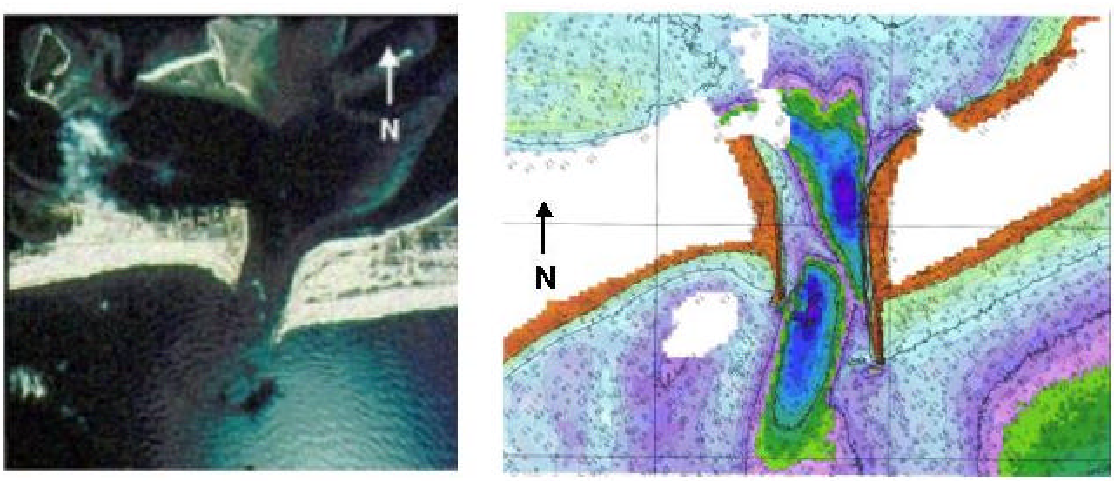

Figure 4.3

4.2 Harbors

Because the SHOALS system is operable from both a helicopter and a fixed wing aircraft. it is equally effective at evaluating small harbor projects. The SHOALS mission at Rye Harbor in New Hampshire was collected from the Bell 212 platform. The survey gives detailed bathymetry and topography of the entrance channel and harbor interior including the entrance breakwaters and adjacent upland areas (Figure 4.4). From these data dredging requirements for both the channel and harbor interior are accurately assessed. The survey sampled 0.3 km^2 with 15,000 laser soundings.

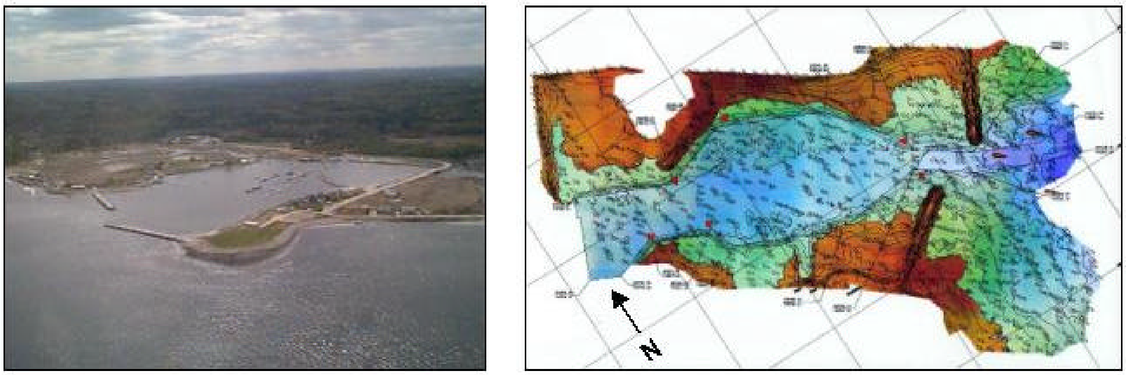

Figure 4.4

Port Huron (Figure 4.5) is also a small project, but it was surveyed as a part of a 4.5-km^2 regional survey of Lake Huron in Michigan. Port Huron is about 75m X 90m. Sediment processes on the coast of Lake Huron cause a tremendous amount of shoaling, and therefore dredging, at the port. The USACE Waterways Experiment Station Coastal and Hydraulics Laboratory has used the SHOALS data collected at Port Huron to build a physical model. The model will yield a greater understanding of processes in the area, and will perhaps lead to a cost-effective solution to the shoaling problem.

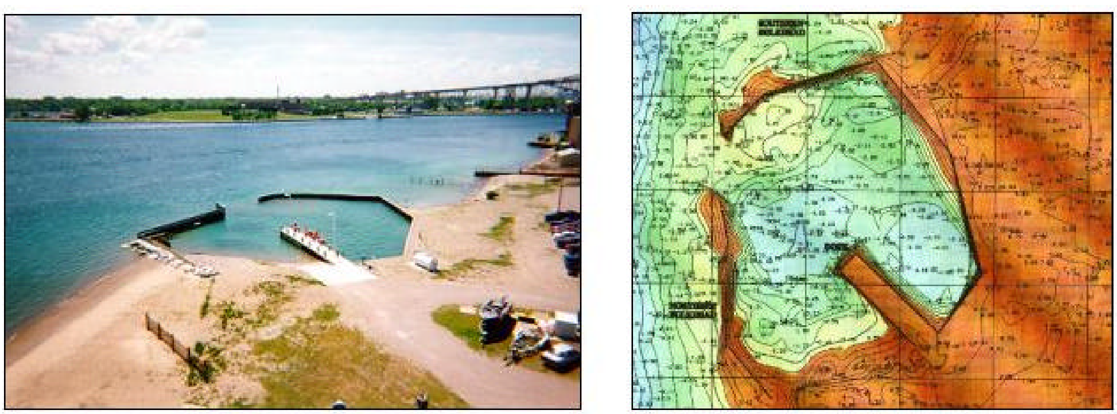

Figure 4.5

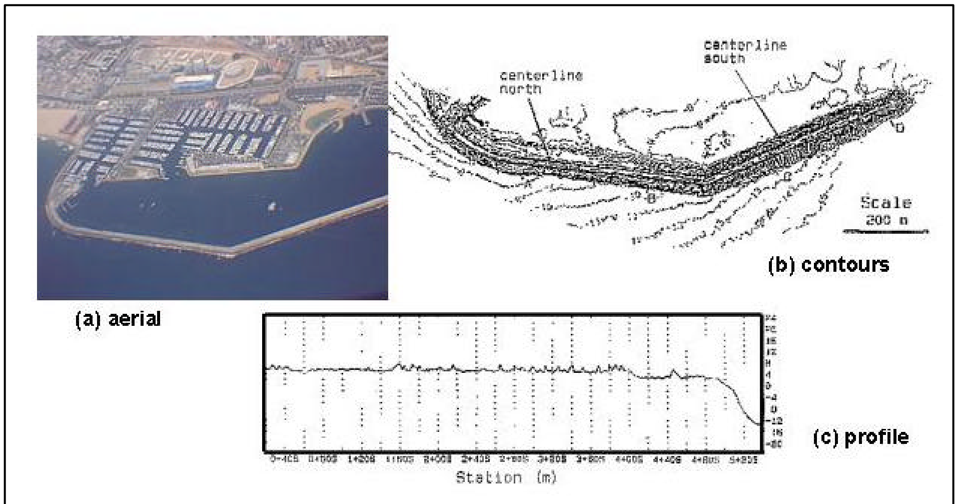

Figure 4.6

In August 1996, SHOALS surveyed King Harbor at Redondo Beach, California. This harbor is entirely man-made and protected from wave energy by two rubble-mound breakwaters. The primary objective of this SHOALS mission was to survey the breakwaters to quantify structural damage from wave overtopping. The survey was complete within one hour and included over 15,000 soundings on the breakwaters alone. Contours of the breakwaters show the north breakwater's position and shape both above and below the waterline (Figure 4.6). The centerline cross-sections reveal areas with low crest elevations, particularly at the structure's tip. Cross-sections taken perpendicular to the structure’s centerline show slope adjustments and relocation of armor stone. The information provided by SHOALS allows maintenance personnel to reliably assess the condition of the breakwaters and identify whether repairs are warranted.

5.0 NAUTICAL CHARTING

To date, five SHOALS surveys were collected specifically for the creation of nautical charts. In 1996, SHOALS completed its first mission outside the United States: along the Yucatan Peninsula, Mexico (Figure 5.1). This 800-km^2 survey, SHOALS largest to date, was collected for the US Naval Oceanographic Office. During the 56-day deployment required to complete this survey, SHOALS collected over 100 million depth soundings (POPE et al., 1997) As with any charting effort, accurate identification of potential navigation hazards was essential to this mission. Aside from numerous coral heads located during the survey, SHOALS data also located and mapped two previously uncharted shipwrecks. In addition to depth measurements, positions of above-water features such as piers, navigation aids, and lighthouses were retrieved from SHOALS’ geo-referenced video recordings.

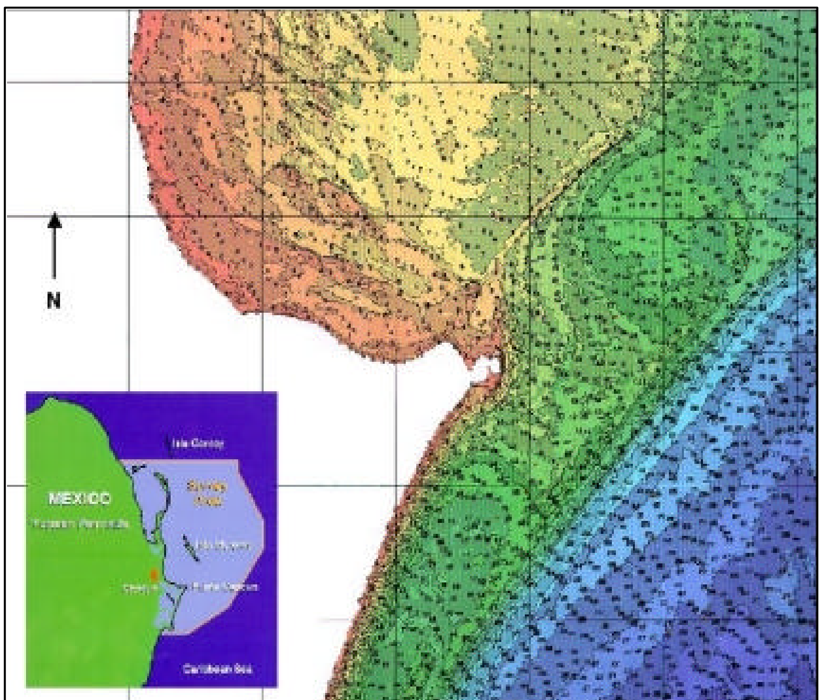

Figure 5.1

6.0 EMERGENCY RESPONSE

The speed of data collection with the SHOALS system makes it an ideal tool for emergency response. SHOALS' first mission in this capacity was at East Pass, a tidal inlet located on the Florida Panhandle near Destin. Hurricane Opal, a Category 3 storm, made landfall in this area in October of 1995. A SHOALS survey of East Pass was flown five days later. The survey was completed in about one hour and included over 500,000 soundings through the inlet throat and along the adjacent beaches. A conventional single-beam fathometer survey of the navigation channel only takes five days to complete. The final products developed from the SHOALS survey were given to the emergency response crew within the day. The SHOALS data revealed extensive scouring at the ends of the rubble-mound jetties that stabilize the navigation channel. Navigation channel shoaling on the order of 60,000 m^3 was calculated from the data collected in the inlet throat. Norriego Point, a spit grown across the channel connecting Old Pass Lagoon with the inlet interior, was breached; SHOALS was used to resolve the new position of the shoreline (Fig. 6.1).

Figure 6.1

East Pass has been surveyed three times since the initial post-storm survey. These surveys measure the long-term recovery of the inlet system. By the November 1997 survey (Fig. 6.1) the scour holes had equilibrated, as had sand dredged from the channel and placed on the beaches. Norriego Point had also been rehabilitated with dredged sand, but by 1997 the spit had almost breached again (MCCLUNG, 1998).

7.0 CONCLUSIONS

Laser remote sensing of bathymetry is an integral tool for improving coastal engineering evaluation while maintaining cost-effectiveness. With SHOALS unique ability to collect high-density, synoptic bathymetry and topography of a coastal project, more complete quantitative analysis is possible. At East Pass for example, the SHOALS survey following Hurricane Opal allowed precise determination of unsafe channel depths and allowed accurate calculation of dredging requirements. And repeated SHOALS surveys at Shinnecock Inlet provided the comprehensive coverage necessary to develop a meaningful short-term sediment budget. Another benefit of lidar bathymetry systems is their capability to collect data in very shallow or environmentally sensitive waters that are unreachable using conventional survey methods. For example, rubble-mound structures like the King Harbor breakwater can be fully mapped for assessing the structure’s integrity.

Existing SHOALS surveys encompass a wide variety of project types with purposes spanning from small-scale project management of tidal inlets to large-scale charting of regional coastal waters. Now that lidar bathymetry systems like SHOALS are fully operational, regional approaches to engineering and management of the coastal zone are feasible. Densely spaced coastal measurements of both bathymetry and topography over large regions describe spatial variability of the shoreline position and nearshore and upland morphology. Repeated regularly, regional surveys of this type will give insight to large-scale sediment pathways and transport volumes, promoting a systems approach to coastal management.

The SHOALS program is based at the USACE Joint Airborne lidar Technical Center of Expertise (JALBTCX) in Mobile, Alabama. During 1999, SHOALS missions are scheduled for New Zealand, Hawaii, and the Caribbean Sea. In addition to survey operations, research and development toward improving lidar bathymetry are continued at the JALBTCX. Future development plans include data integration and auxiliary sensor fusion.

REFERENCES

BIRKEMEIER, W.A., MILLER, H.C., WILHELM, S.D., DEWALL, A.E., GORBICS, C.S., 1985. "A User's Guide to the Coastal Engineering Research Center's (CERC's) Field Research Facility, Instructional Report CERC-85-1, US Army Corps of Engineers, Washington, DC.

GUENTHER, G.C., BROOKS, M.W., and LAROQUE, P.E., 1998. "New Capabilities of the "SHOALS" Airborne Lidar Bathymeter," *Proceedings, Fifth International Conference on Remote Sensing for Marine and Coastal Environments,* Environmental Research Institute of Michigan, Oct 5-7, San Diego, CA, pp. 147-55.

GUENTHER, G. THOMAS, R.W.L., and LAROCQUE, P.E., 1996. "Design Considerations for Achieving High Accuracy with the SHOALS Bathymetric Lidar System," *SPIE Selected Papers, Laser Remote Sensing of Natural Waters: From Theory to Practice,* edited by Victor I. Feigles and Yurij I. Kopilevich, St. Petersburg, Russia, vol. 2694, pp. 54-71.

IRISH, J.L., LlLLYCROP, W.J., PARSON, L.E., 1997. "Accuracy of Sand Volumes as a Function of Survey Density," *Proceedings, 25th International Conference on Coastal Engineering,* September 2-6, Orlando, FL, vol. III, pp. 3736-3749.

LlLLYCROP, W.J., PARSON, L.E., and IRISH, J.L., 1996. "Development and Operation of the SHOALS Airborne Lidar Hydrographic Survey System," *SPIE Selected Papers, Laser Remote Sensing of Natural Waters: From Theory to Practice,* edited by Victor I. Feigles and Yuriji. Kopilevich, St. Petersburg, Russia, vol. 2694, pp. 26-37.

MCCLUNG, J.K., 1998. "High Density Lidar Data: A Monitoring Tool for East Pass, FL," *Proceedings, Fifth*

International Conference on Remote Sensing for Marine and Coastal Environments, Environmental Research Institute of Michigan, October 5-7, San Diego, CA, pp. I 75-82.

POPE, R.W., REED, B.A., WEST, G.R., and LlLLYCROP, W.J., 1997. "Use of an Airborne Laser Depth Sounding System in a Complex Shallow-Water Environment,".

RILEY, J.L., 1995 "Evaluating SHOALS Bathymetry Using NOAA Hydrographic Survey Data: *Proceedings 24th Joint Meeting of UNIR Sea Bottom Surveys Panel,* November 13-17, Tokyo, Japan.